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THE COSTS AND BENEFITS OF
AIRCRAFT AVAILABILITYMatthew S. Goldberg, *Project Leader*
Karen W. Tyson

March 1991

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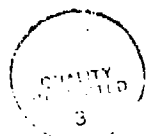
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PREFACE

This paper was prepared by the Institute for Defense Analyses (IDA) under IDA's Independent Research Program. The objective of the task was to derive a method of estimating tactical aircraft costs that takes into account the variable of system reliability.

This work was reviewed within IDA by Stanley A. Horowitz, Thomas P. Frazier, and Jeffrey H. Grotte.



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I. INTRODUCTION

A. BACKGROUND

The military value of a weapon system depends critically on its reliability and maintainability. The Department of Defense (DoD) has initiated a Total Quality Management (TQM) program to promote efforts to enhance the overall quality of its weapon systems. In addition, a previous study at the Institute for Defense Analyses concluded that improving the reliability of a weapon system leads to both increased combat capability and reduced support costs [1].

When deciding how much reliability to demand in new systems, DoD must be able to estimate the cost implications of designing and manufacturing higher quality equipment. Moreover, this information is required at an early stage in the acquisition cycle, so that design and manufacturing processes may be influenced by the cost tradeoffs.

Although the benefits are clear, the costs of achieving reliability improvements have not previously been quantified. For example, standard cost-estimating relationships (CERs) examine the cost implications of purchasing greater technical performance. In the case of tactical aircraft, performance is usually measured by the aircraft's weight and speed. To our knowledge, however, no aircraft CERs have been estimated that account for component or system reliability.

B. APPROACH

This paper describes a method for incorporating system reliability into cost estimates for tactical aircraft. The emphasis is on tactical aircraft because the cost data are readily available, and because there is a great deal of received knowledge on the determinants of these costs.¹ The cost of reliability may be incurred during either the development or procurement phase in the life cycle of an aircraft program. This cost must be balanced against the benefits of increased combat capability and reduced support costs.

¹ Recent studies at IDA have examined development [2] and operations and support [3] costs; a recent study at RAND [4] has examined development and procurement costs. See also the references therein.

We analyzed data on eleven Navy and Air Force tactical aircraft models, covering most of the 1980s. We used fleet-wide mission-capable (MC) rates as our measure of reliability. The MC rate reflects both the level of reliability designed and manufactured into the system, and the maintenance efforts applied to the fielded system. In order to separate these two factors, we developed a system of two regression equations.

The first equation in our system predicts the fleet-wide MC rate by aircraft model. The drivers in this equation are aircraft characteristics, development costs, and unit procurement costs. The respective coefficients on development and procurement costs measure the increases in availability associated with unit (i.e., one-million constant dollar) increases in these costs. The reciprocals of these coefficients measure the marginal costs of a unit increase in the MC rate.

We estimated two distinct marginal costs, one for improvements in the MC rate engendered by increased development spending, and another for improvements engendered by increased procurement spending. No presumption was made that the two marginal costs are equal. Indeed, a major goal of this research was to determine in which of these two phases the costs of reliability are borne.

We also estimated a second regression equation, one that predicts fleet-wide operations and maintenance (O&M) costs by aircraft model. The cost drivers in this equation are aircraft characteristics, plus the MC rate as predicted by the first regression equation. The coefficient on the MC rate may be used to compute the life-cycle savings in O&M costs associated with an increase in aircraft availability. These savings may then be balanced against the marginal cost of an MC point, in order to evaluate the cost-effectiveness of investments that improve reliability.

Section II of this paper reviews an alternative approach for assessing reliability investments that involves before-and-after comparisons for a given aircraft model rather than comparisons across aircraft models. Section III describes the data used in the current approach. Section IV presents the regression equation for the MC rate, and Section V presents the regression equation for O&M costs. Section VI combines the results of the two equations, and evaluates the costs and benefits of reliability investments. Finally, Section VII contains our conclusions.

II. LITERATURE REVIEW

A comparison across aircraft models is not the only possible approach for estimating the costs and benefits of aircraft reliability. An alternative approach is a before-and-after comparison for a given aircraft model. This approach is exemplified in a RAND study by Arthur Alexander, who examines reliability improvement programs [5]. He states on p. 4:

The analytical benefits of examining reliability improvement programs lie in their control of extraneous variables. Both "before" and "after" reliability measures can be obtained, as well as the cost of producing the change. Also, applying the same data collection system and the same definitions reduces the often serious measurement problems associated with evaluating reliability.

However, he inserts the following caution regarding his approach:

Under certain conditions, data generated by reliability improvement programs can lead to biased estimates of the cost of reliability, which may suggest that reliability is cheaper to obtain, in general, than is actually the case. Such a downward bias exists for those programs where field experience demonstrates lower reliability levels than had been planned, and where an improvement program is subsequently undertaken. Reliability improvement costs in these cases will reflect actual costs, but *they will produce underestimates of projected costs because only those projects with sufficiently low costs or high returns will actually be selected as reliability improvements and thus enter into the database* [emphasis added]. Downward biases in cost estimates are also produced by exogenous technological improvements over time that shift the cost-reliability relationship at no expense to the examined project.

Alexander reaches two broad conclusions regarding reliability improvements. First, he argues on p. 11 that reliability may be increased by accepting reductions in system performance:

It is now generally accepted that for given development resources, pushing the state of the art in seeking high operational performance will also result in unreliable systems. One method for increasing reliability, therefore, is to back off on performance requirements to reduce component stress. Reduced performance is a price that can be paid for higher reliability and is symmetrical with development and production costs in its potential effects. New technology can ease these tradeoffs. . . . Technology can loosen constraints, but it does not eliminate the need for assigning priorities and considering tradeoffs.

Second, Alexander argues that higher *production* costs are not a necessary consequence of increased reliability. He states on p. 19:

The data on the effect of reliability improvement on unit production costs show that, in most cases, production cost changes were zero. Indeed, in one case examined in detail, the F100 engine Component Improvement Program (CIP), the production unit cost changes were negative—the engine became less costly to produce as a result of the CIP changes. For the Navy's F/A-18 fighter aircraft, we estimated [using CERs] a small production cost effect of 1.6-2.6 percent on the basis of greater weight of the aircraft attributed by the developers to reliability. In some cases, possible production cost increases may have been compensated for by cost reductions arising from learning curve effects, or by contractors absorbing additional costs in reduced profits. *Apparently, when reliability is a high-priority design goal—either in a new program or in a post-development reliability improvement program—the bulk of the cost effects are in non-recurring investments rather than in recurring production costs* [emphasis added].

A major goal of our research was to test Alexander's conjecture that the costs of reliability are borne during the development phase rather than during the procurement phase.

III. DATA

Six of the eleven aircraft models studied pertain to the Navy and Marine Corps: A-6E, A-7E, AV-8B (Marine Corps), F-14A, F/A-18 (A and B series, Navy and Marine Corps combined), and S-3A. The remaining five aircraft models pertain to the Air Force: A-10A, F-15 (A through D series combined), F-16 (A through D series combined), F-111 (A, D, E, and F series combined), and EF-111A.

The data used in this paper on those aircraft fall into three major categories: aircraft characteristics, aircraft costs, and fleet utilization. The three categories are discussed in turn.

A. AIRCRAFT CHARACTERISTICS

Table 1 presents the aircraft characteristics used in the analysis. All of the Navy aircraft, except the AV-8B, are designed primarily for operation off aircraft carriers. We expect that carrier operations will be associated with both lower aircraft availability and higher O&M costs. These hypotheses follow from the austere operating environment and the corrosive effects of saltwater.

The empty weight, maximum speed (at any altitude), and year of initial operational capability (IOC) are taken from Nicholas and Rossi [6]. In cases where we have combined more than one aircraft series, the data refer to the earliest aircraft series in the group. Empty weight is defined as the weight of the aircraft (in pounds), with no fuel, ordnance, lubricants, or crew aboard. For comparability with other studies of aircraft costs, we have converted Nicholas and Rossi's speed figures from miles per hour to knots.

The advanced materials column gives the percentage of the airframe structural weight² that consists of titanium and composites. Except for the A-7, these figures are taken from Harmon et al. (Reference [2], Table 8). The figure for the A-7 is taken from Hess and Romanoff (Reference [4], Table 4).

² Structural weight is defined to include the wings, tail, body, alighting gear, and engine section.

Table 1. Aircraft Characteristics

Aircraft	IOC (Year)	Aircraft Carrier ^a	Empty Weight (Pounds)	Maximum Speed (Knots)	Advanced Materials (Percent)
Navy/marine Corps					
A-6E	1972	1	26,273	559	1
A-7E	1970	1	19,403	562	9
AV-8B	1985	0	12,500	594	34
F-14A	1972	1	40,100	1,518	31
F/A-18	1982	1	23,050	— ^b	23
S-3A	1975	1	26,650	450	3
Air Force					
A-10A	1977	0	20,800	450	10
F-15	1975	0	28,000	1,650	37
F-16	1980	0	16,126	1,320	6
F-111	1967	0	46,712	1,452	2
EF-111A	1983	0	55,275	1,196	2

^a 1 = yes; 0 = no.

^b Value is omitted because of classification.

B. AIRCRAFT COSTS

The data on aircraft costs fall into three major categories: research, development, test and evaluation (RDT&E); procurement; and operations and maintenance (O&M). The three categories are discussed in turn.

1. RDT&E Costs

RDT&E costs for each aircraft were taken from the funding summary page of the most recent available Selected Acquisition Report (SAR) [7]. In the case of the A-7E and the F-111, the SARs were unavailable or incomplete, so development costs were taken instead from Nicholas and Rossi [6]. Spending in each year was converted to millions of FY 1991 dollars using OSD deflators for Navy and Air Force RDT&E, as appropriate.

Because our purpose was to test the impact of early development spending on reliability, we did not include spending for modification programs. Spending after the time of the aircraft's IOC was assumed to be for modification programs. In the future, we think it is important to make an effort to examine specific modification programs.

The RDT&E costs are presented in Table 2.

Table 2. Development and Procurement Costs
(Millions of FY 1991 Dollars)

<u>Aircraft</u>	<u>RDT&E Cost (through IOC)</u>	<u>Total Procurement Cost (100th unit)</u>
Navy/Marine Corps		
A-6E	120.5	31.31
A-7E	177.8	14.11
AV-8B	1,800.0	22.99
F-14A	3,853.1	38.06
F/A-18	4,116.5	54.60
S-3A	2,681.2	40.94
Air Force		
A-10A	1,101.9	13.83
F-15	5,759.5	34.62
F-16	1,742.5	26.61
F-111	2,997.4	44.19
EF-111A	362.9	29.06

2. Procurement Costs

The data collected on total procurement costs (also shown in Table 2) include: flyaway costs, ground support equipment, support costs (publications, data, training), advanced procurement, peculiar support costs, initial spare parts, initial repair parts, allowances for engineering changes, warranties, and first-destination transportation.

Other measures of cost were considered, including flyaway cost in the SARs and weapon system cost in Nicholas and Rossi [6]; however, total procurement was the only cost available uniformly for all aircraft. Total procurement cost was also considered the most appropriate measure because it is the most inclusive. For example, total procurement includes program management expenses, which might be higher if a major effort were made in the program office to enhance reliability and maintainability.

Annual procurement costs and quantities for the A-6E, AV-8B, F-14A, F/A-18, F-15, F-16, and EF-111A were taken from the SARs. Costs for the A-7E, S-3A, A-10A, and F-111 were not available in the SARs, and were taken instead from Nicholas and Rossi [6]. Some of these programs acquired hundreds of aircraft, while others acquired very few (for example, only 42 for the EF-111A). In order to standardize our cost measure across programs, we estimated the cost of the 100th unit. For those systems for which annual

data were available, we computed the average cost in the year in which the 100th unit was procured. For the remaining systems, Nicholas and Rossi gave only a single, cumulative procurement quantity and a corresponding total cost. For these systems, we estimated the cost of the 100th unit using a price-improvement curve. We assumed a learning rate of 90 percent, a rate commonly achieved in aircraft programs.

Then-year costs were converted to millions of FY 1991 dollars using OSD deflators for Navy and Air Force aircraft procurement.

3. Operations and Maintenance Costs

The O&M data derive from information contained in various annual releases of the Department of Defense Five Year Defense Program (FYDP). The FYDP data are documented in [8]. In connection with previous studies, the Institute for Defense Analyses has collected FYDP data back through FY 1971.

The FYDP data are organized by program element (PE) and resource identification code (RIC). For the systems that we consider, with one exception to be noted below, each relevant PE pertains to at most one aircraft model. Conversely, as shown in Table 3, some of the aircraft models are associated with multiple PEs. For example, F-15 air defense and tactical squadrons have distinct PEs.

The exception arises when considering readiness or training squadrons. The O&M dollars for Navy readiness squadrons, other than S-3 squadrons, are reported in a single PE, 0204156. Similarly, the O&M dollars for Air Force training squadrons, other than F-15 air defense squadrons, are reported in PE 0207597. We allocated these training dollars to individual aircraft models using an algorithm that will be described presently.

We extracted data based upon RIC as well as PE. The relevant O&M RICs for Active forces are 0511 (Navy), 0512 (Marine Corps), and 0513 (Air Force). The conjunction of these RICs plus the PEs listed in Table 3 yielded annual O&M figures, which we converted to thousands of FY 1991 dollars using OSD deflators for Navy and Air Force O&M. In addition, numerous RICs describe numbers of aircraft (as opposed to dollar expenditures). We extracted data from these RICs as well, for later use in normalizing flight hours into utilization rates per aircraft.

The RICs for numbers of aircraft also enabled us to allocate the training dollars to individual aircraft models. A naive approach would allocate training dollars in proportion to the numbers of aircraft found in training squadrons. Suppose, for example, that 10

percent of all Air Force training aircraft were A-10s. The naive approach would allocate 10 percent of the annual training budget to A-10s.

Table 3. Program Elements

Aircraft	Program Element	Description
Navy		
A-6E	0204134	Operational Squadrons
A-7E	0204135	Operational Squadrons
F-14A	0204144	Operational Squadrons
F/A-18	0204136	Operational Squadrons
S-3A	0204234	Operational Squadrons
	0204262	Readiness Squadrons
Readiness Squadrons ^a	0204156	
Marine Corps		
AV-8B	0206110	Operational Squadrons
	0206497	Training Squadrons
F/A-18	0206134	Operational Squadrons
	0206493	Training Squadrons
	0206497	Training Squadrons
Air Force		
A-10A	0207131	Tactical Squadrons
F-15	0102116	Air Defense: Operational Squadrons
	0102897	Air Defense: Training Squadrons
	0207130	Tactical Squadrons
F-16	0207133	Tactical Squadrons
F-111	0207129	Tactical Squadrons
EF-111A	0207252	Tactical Squadrons
Training Squadrons ^b	0207597	

^a All aircraft models except S-3A.

^b All aircraft models except F-15.

A more refined approach recognizes that aircraft models differ in their annual O&M costs per individual aircraft (i.e., per tail-number). This approach allocates training costs based on *weighted* numbers of aircraft, where the weights reflect the relative costs of operating each respective aircraft model.

Specifically, suppose we have T dollars of training costs to allocate in a particular fiscal year. We index aircraft models by $k=1, \dots, K$. Suppose there are N_k aircraft of model k in operational squadrons, and let C_k denote total O&M expenditures in these squadrons. Hence C_k/N_k measures the annual cost of operating a single aircraft of model k . Suppose also that there are M_k aircraft of model k in training squadrons.

We assume that the annual cost per aircraft is the same in both operational and training squadrons, so operating M_k training aircraft should cost $M_k C_k / N_k$ per year. The proportion of annual training costs attributed to model k is as follows: $P_k = (M_k C_k / N_k) / \sum_j M_j C_j / N_j$. This proportion may be further expressed as: $P_k = M_k w_k / \sum_j M_j w_j$, where $w_j = (C_j / N_j) / \sum_i (C_i / N_i)$ and $\sum_j w_j = 1$. Using these proportions,³ we allocated training costs of $P_k T$ to aircraft model k . These costs were added to the costs of the PEs directly associated with each respective aircraft model.

C. FLEET UTILIZATION

The Navy data on fleet utilization were obtained from the Assistant Chief of Naval Operations (Air Warfare), Naval Aviation Maintenance Program Division, Readiness Analysis Branch (OP-515). The corresponding Air Force data were obtained from Deputy Chief of Staff (Logistics and Engineering), Directorate of Maintenance and Supply, Weapon System Support Division, Aircraft Branch (LEXY).

These data describe the mission-capable (MC) rates and annual flight hours by aircraft model and year. The mission-capable rate is defined as $(EIS - NMC) / EIS$, where EIS = equipment-in-service hours, and NMC = total hours not mission-capable, whether due to scheduled maintenance, unscheduled maintenance, or supply (i.e., awaiting parts) [9]. Annual flight hours represent a total over the entire fleet, including both operational (deployed and non-deployed) and training squadrons.

The data on flight hours were used to normalize O&M dollars into O&M per flight hour. The latter variable measures the cost of operating a particular aircraft model. Flight hours were themselves normalized by the number of aircraft (from the FYDP data) to construct flight hours per aircraft per year. This variable is interpreted as an aircraft utilization rate.

Table 4 presents the MC rate, O&M cost per flight hour, and flight hours per aircraft per year, averaged across the years in our sample for each aircraft model. Appendix A presents the detailed annual data that were used in computing these average figures.

³ By contrast, the naive approach replaces P_k with $Q_k = M_k / \sum_j M_j$. This approach implicitly assigns each aircraft model an equal weight w_k so that costs are allocated in proportion to aircraft numbers with no adjustment for relative operating cost.

Table 4. Average Utilization Data by Aircraft Model

Aircraft	Begin-Year	End-Year	MC Rate	O&M per Flight Hour (Thousands of FY 1991\$)	Flight Hours/ Aircraft/Year
Navy/Marine Corps					
A-6E	1981	1989	64.63	2.527	511.1
A-7E	1981	1989	63.91	1.827	465.1
AV-8B	1984	1989	73.90	0.151	222.4
F-14A	1981	1989	62.63	2.970	376.9
F/A-18	1982	1989	68.14	1.691	350.8
S-3A	1981	1989	64.44	2.795	467.9
Air Force					
A-10A	1983	1989	82.10	0.913	587.4
F-15	1983	1989	76.77	2.982	324.5
F-16	1983	1989	81.70	1.621	387.0
F-111	1983	1989	69.70	2.970	293.1
EF-111A	1983	1988	67.88	2.320	298.1

The data elements just described are used in the next two regression models. The first regression model predicts the fleet-wide MC rate, and the second regression model predicts O&M cost per flight hour.

IV. THE MC EQUATION

We use the MC rate as our measure of aircraft availability. An alternative measure would be the mean time between failures (MTBF) for an individual aircraft tail-number. However, the MTBF fails to distinguish "important" from "unimportant" failures, either in terms of the degree of mission degradation or the time to repair (i.e., the hours of availability lost). By contrast, the MC rate incorporates both failure rates and repair rates; the MC rate can be high if components are designed with low failure rates, or if they have moderate failure rates but are designed to be easily repaired.

A. MODEL SPECIFICATION

The first equation in our model predicts the MC rate. The data on MC rate pertain to each aircraft model for a period of years after the aircraft reached IOC. Therefore, it is reasonable to view the MC rate as a function of the RDT&E costs incurred prior to IOC (recall that we truncated RDT&E costs at IOC). The MC rate is also a function of procurement cost and aircraft characteristics.⁴

It would be inappropriate to model the MC rate as a linear function of aircraft costs and characteristics. Although observed MC rates are at most 100 percent, a linear function might predict MC rates above 100 percent for aircraft with sufficiently favorable characteristics.

Instead, as described in Appendix B, we used the exponential function $MC = f(X) = 100[1 - \exp(-b_0 - b_1X)]$. In this function, X is a vector of aircraft costs and characteristics, b_1 is a vector of coefficients, and b_0 determines the intercept. The exponential function is strictly increasing and concave in the product b_1X , and approaches the limit 100 as b_1X approaches infinity.

We demonstrate in Appendix B that the partial derivative of the exponential function with respect to a particular aircraft characteristic, X_j , is not simply equal to the

⁴ The presence of time-invariant aircraft characteristics in the equation precludes inclusion of dummy variables for aircraft model. We demonstrate in Appendix B that inclusion of dummy variables would lead to perfect collinearity and, hence, failure of the estimation procedure.

corresponding coefficient, b_j . Rather, it is equal to $100 b_j \exp(-b_0 - b_1 X) = (100 - MC) b_j$. This quantity is often evaluated at the sample mean of MC.

Finally, Appendix B develops a transformation of the MC rate that is linearly related to the aircraft costs and characteristics, X. In particular, a linear regression of $Y = g(MC) = -\ln[1 - (MC/100)]$ on the set of X values yields estimates of b_0 and b_1 .

The prediction errors from the regression are likely to be autocorrelated. There are well-known procedures for both measuring the degree of autocorrelation, and correcting the problem to secure efficient estimates. However, these procedures must be modified when the data set consists of pooled time-series on several aircraft models. The appropriate modifications are also described in Appendix B.

B. FINDINGS

(U) The estimated MC equation is reported in Table 5. The regression fits the data quite well, with an R-squared statistic of .511. A correction for autocorrelation was performed, using an autocorrelation coefficient of .845.

Table 5. Regression for MC Rate

Variable	Mean	Standard Deviation	Regression Coefficient	Standard Error	T-Statistic	Partial Derivative
Dependent						
MC Rate	69.93	9.69				
$-\ln(1-(MC/100))$	1.2544	0.3331				
Independent						
Intercept	1.0	0.0	0.5160	0.0165	31.271	
Aircraft Empty Weight	28,406	12,053	-0.0000052	0.0000048	-1.085	-0.000157
Dummy Variable, Aircraft Carrier	0.5181	0.5027	-0.5430	0.1236	-4.394	-16.33
Years Since IOC	9.81	5.64	0.0340	0.0099	3.450	1.022
Percent Advanced Materials	14.19	13.30	0.0191	0.0057	3.362	0.5730
Total Development Cost (Through IOC)	2,240.1	1,765.8	-0.000183	0.000062	-2.952	-0.00551
Procurement Cost (100th unit)	32.08	12.14	0.0304	0.0069	4.416	0.9133

Notes: n=83, R-squared=.511, based on autocorrelation correction rho=.845.

The partial derivatives in Table 5 were all computed at the sample average MC rate of 69.93. For example, holding all other variables constant, the model predicts that carrier-based aircraft will suffer a 16-point loss in mission-capability compared to land-based aircraft. The 16-point differential is roughly consistent with the sample averages reported in Table 4. That table revealed that carrier-based aircraft have MC rates in the low- to mid-60s, while land-based aircraft often display MC rates over 70 and even over 80.

Availability appears to improve with system age. Specifically, the model predicts an improvement of about one MC point per year. The model also predicts that aircraft containing a greater proportion of advanced materials have higher MC rates. Each percentage-point increase in the advanced materials content is associated with an improvement of about one-half MC point.

The effect of procurement cost has the expected positive sign, and is statistically significant. A \$1 million increase in unit procurement cost is associated with an increase of nearly one MC point. Taking reciprocals, the marginal cost of an MC point is \$1.1 million. In a later section, we compare this figure to the savings that accrue from the additional MC point.

The effect of development cost is negative and statistically significant. The negative sign is unexpected, implying that greater development effort leads to lower availability. However, the magnitude of this effect is almost negligible. For example, a \$200 million increase in development cost (almost 10 percent of the sample mean) is associated with a drop of barely one MC point.

Although this magnitude is small, the perverse negative sign does require further explanation. One possibility is that most RDT&E dollars are spent on problems other than reliability and maintainability (R&M). These RDT&E dollars could conceivably improve R&M, if they were specifically earmarked for that purpose. However, R&M problems are often not apparent until the aircraft reaches the field, at which point most of the RDT&E budget has already been expended.

When R&M problems do arise in the field, they are often attacked using procurement dollars rather than RDT&E dollars. In particular, the portion of total procurement cost in excess of flyaway cost consists of support costs that directly address

R&M concerns.⁵ Therefore, part of the expected effect of development cost on MC rates may show up indirectly through the effect of procurement cost.

Finally, because we truncated our development cost stream at IOC, we did not capture the effects of post-IOC reliability improvement programs. The importance of these programs was emphasized by Alexander [5], who concluded (p. 19) that "the bulk of the cost effects [of reliability improvement programs] are in non-recurring investments rather than in recurring production costs."

⁵ Frazier et al. [10], Table V-1, analyze the components of total procurement cost for the F-16. They report that, over the years FY 1986-1989, total procurement cost exceeded flyaway cost by between 12 and 18 percent. The largest single component of this difference was airframe peculiar ground support equipment. On a per-aircraft basis, this component alone was over 10 percent of the flyaway cost of an F-16 in FY 1986.

V. THE O&M EQUATION

A. MODEL SPECIFICATION

The second equation in our model predicts O&M dollars per flight hour. We view this variable as a measure of the cost of maintaining a particular aircraft model. We express the relationship between cost, weight, and speed as a power function, $O\&M = X^b$. This relationship is easily estimated using the natural logarithms of cost, weight, and speed. We include several additional cost drivers in linear (not logarithmic) form. These cost drivers are flight hours per aircraft per year (a measure of aircraft utilization), a dummy variable for carrier-based aircraft, and years since IOC.

We hypothesize that more reliable aircraft have lower O&M costs. Indeed, it is this effect that must be balanced against the marginal procurement cost of an MC point, in order to determine the cost-effectiveness of investments that improve reliability. However, care must be exercised in attempting to estimate this relationship. Although a higher MC rate reflects a more reliable (and thus more cheaply maintained) aircraft, increases in O&M expenditure can compensate for otherwise poor reliability. Hence there is reverse causation flowing from O&M (the left-hand variable) to MC (a right-hand variable). Moreover, because increases in O&M lead to *increases* in MC, the effect of O&M on MC differs in sign as well as causation from the effect of MC on O&M. The negative coefficient that we expect on MC is offset and possibly even overturned by the reverse causation.

This problem is alleviated by replacing MC with a proxy variable that is highly correlated with MC, yet immune from reverse causation. A proxy variable satisfying these requirements is said to be an "instrumental variable" for MC. A natural instrumental variable is given by the value of MC predicted from the model reported in Table 5. This variable is clearly correlated with MC, because the underlying regression has a high R-squared statistic. The instrumental variable does not suffer from reverse causation, because it is determined solely by aircraft characteristics and *historical* costs, not by contemporaneous O&M expenditures.

The instrumental variable may be interpreted as a "benchmark" level of availability, reflecting the intrinsic availability of the aircraft, yet unaffected by compensating maintenance actions in the field. Stated differently, the instrumental variable is

uncontaminated by the reverse causation that leads to biased estimates when using the raw MC rate in the O&M regression.⁶

B. FINDINGS

The estimated O&M equation is reported in Table 6. The regression fits the data quite well, with an R-squared statistic of .672. A correction for autocorrelation was performed, using an autocorrelation coefficient of .364.

Table 6. Regression for O&M Dollars per Flight Hour

Variable	Mean	Standard Deviation	Regression Coefficient	Standard Error	T-Statistic
Dependent					
O&M/Flight Hours	2.121	1.048			
ln(O&M/Flight Hours)	0.4990	0.9542			
Independent					
Intercept	1.0	0.0	-11.2591	1.2622	-8.920
ln(Aircraft Empty Weight)	10.171	0.4072	0.9595	0.2168	4.425
ln(Aircraft Speed)	6.772	0.5056	0.7787	0.2044	3.809
Flight Hours/Aircraft/Year	397.5	114.6	0.0020	0.0010	1.981
Dummy Variable, Aircraft Carrier	0.5181	0.5027	0.3095	0.2223	1.392
Years Since IOC	9.81	5.64	0.0981	0.0209	4.692
Predicted MC Rate	69.88	6.78	-0.0743	0.0158	-4.688

Notes: n=83, R-squared=.672, based on autocorrelation correction rho=.364.

The coefficient on aircraft weight is essentially 1.0. Because both cost and weight are measured in logarithms, the coefficient of 1.0 implies a proportional relationship between these two variables. Hence a given percentage increase in weight is associated with an equal percentage increase in O&M per flight hour.

The coefficient on aircraft speed is somewhat lower, .7787. That relationship between these two variables is increasing but concave. A given percentage increase in speed is associated with a smaller percentage increase in O&M per flight hour.

⁶ In Appendix B, we present more details on the use of instrumental variables. We demonstrate that the predictions obtained from the MC regression are slightly biased, due to the non-linearity of the transformation employed in estimating that model. However, we also derive a simple correction to the intercept that removes the bias, at least in large data samples.

Increased aircraft utilization is associated with a modest increase in O&M per flight hour. In addition, holding all other variables constant, O&M per flight hour is 36.3 percent higher for carrier-based aircraft than for land-based aircraft.⁷

We found earlier that MC rates improve with system age. Holding the MC rate constant, however, O&M costs increase with system age at the rate of about 10 percent per year.⁸

A one-point increase in the predicted MC rate (our benchmark measure of availability) is associated with a reduction in O&M costs of about 7 percent. This effect is statistically significant, and its magnitude will be examined more closely in the next section to determine the cost-effectiveness of investments in reliability.

We have asserted that the predicted MC rate is a better measure than the raw MC rate, because the latter suffers from reverse causation. We tested this assertion by estimating alternative regression models that contain the raw MC rate. In Table 7, the first model simply repeats the coefficient on the predicted MC rate from the previous table. The second model is identical except that the raw MC rate replaces the predicted MC rate. The coefficient on the raw MC rate is essentially zero. Apparently, the negative effect of intrinsic availability on O&M costs is perfectly offset by the positive effect of O&M expenditures on the raw MC rate.

Finally, the third model contains both the predicted and raw MC rates. Hausman [11] has devised a test to determine whether or not a right-hand variable is "endogenous" (i.e., suffers from reverse causation). According to Hausman's test, the actual MC rate is endogenous if, in a regression containing both variables, the predicted MC rate is significantly different from zero. Our estimates confirm that this is the case. Therefore, unbiased estimates of the uni-directional effect of availability on cost can be obtained only from the regression containing the predicted MC rate (model 1).

⁷ Taking anti-logs, a carrier-based aircraft contributes a multiplicative factor of $e^{.3095} = 1.363$ to the prediction of O&M per flight hour. This represents a 36.3-percent increase relative to land-based aircraft.

⁸ Again taking anti-logs, each additional year of age contributes a multiplicative factor of $e^{.0981} = 1.103$.

Table 7. Alternative Estimates of Coefficient on MC Rate

	Predicted MC Rate	Actual MC Rate
Model 1		N/A
Coefficient	-0.0743	
Standard Error	0.0158	
T-Statistic	-4.688	
Model 2	N/A	
Coefficient		0.0037
Standard Error		0.0156
T-Statistic		0.239
Model 3		
Coefficient	-0.0970	0.0418
Standard Error	0.0169	0.0144
T-Statistic	-5.734	2.909

Note: N/A means not applicable.

VI. COST-EFFECTIVENESS ANALYSIS OF RELIABILITY INVESTMENT

A. HYPOTHETICAL AIRCRAFT

We reported earlier that, holding all other variables at the sample mean, the marginal cost of an MC point is \$1.1 million. We also reported that a one-point increase in the MC rate is associated with a reduction in O&M costs of about 7 percent. From the latter figure, one could apparently compute the life-cycle cost savings that accrue from an investment in reliability, and compare these savings to the marginal cost of \$1.1 million.

This comparison would be misleading, however, because it ignores the non-linearity in the underlying cost and benefit functions. The functional forms that we have chosen for the two regression models reflect increasing marginal cost and decreasing marginal benefit to investments in reliability. These conditions are required to obtain a finite solution for the optimal level of investment. If the marginal cost and marginal benefit were each a constant, and if the latter were larger than the former, then it would pay to continue investing in reliability until the MC rate approached 100 percent. If, on the other hand, the two quantities were each constant but the marginal cost were larger, then it would pay to "disinvest" until the MC rate approached zero.

We noted previously that the functional form of the MC equation is concave. Hence, equal increases in unit procurement cost lead to diminishing increments in the MC rate; conversely, the marginal cost of an MC point is increasing. Similarly, the relationship between O&M cost and the MC rate (holding all other variables constant) is of the form $O\&M = \exp(-b MC)$, which is decreasing and convex. Equal increases in the MC rate lead to reductions in O&M cost that decrease in absolute value.

A proper evaluation of cost-effectiveness must account for the non-linearity in these functions. To illustrate the procedure, we consider a hypothetical, carrier-based attack aircraft of weight 25,000 pounds and speed 600 knots. The partial derivative of the MC rate with respect to unit procurement cost is equal to $(100 - MC)$ times the regression

coefficient of .0304. The marginal cost of an MC point is given by the reciprocal of this product. The first two columns of Table 8 give the MC rate and the marginal cost in the range of 65 to 73 MC points. Note that the marginal cost refers to an increase from the current MC level to the next MC level. For example, the marginal cost of increasing the MC rate from 65 to 66 points is equal to \$0.94 million.

Table 8. Simulation of Costs and Benefits of Reliability Investment

MC Rate	Marginal Cost	O&M Saving	Procurement Saving	Marginal Benefit	Marginal Net Benefit	Cumulative Cost	Cumulative Benefit	Cumulative Net Benefit
65	0.940	1.137	0.455	1.592	0.652	0.940	1.592	0.652
66	0.967	1.056	0.462	1.518	0.550	1.907	3.109	1.202
67	0.997	0.980	0.469	1.449	0.453	2.904	4.559	1.655
68	1.028	0.910	0.477	1.387	0.359	3.932	5.946	2.014
69	1.061	0.845	0.485	1.330	0.269	4.993	7.275	2.282
70	1.096	0.784	0.493	1.277	0.181	6.090	8.553	2.463
71	1.134	0.728	0.501	1.229	0.095	7.224	9.782	2.558
72	1.175	0.676	0.510	1.186	0.011	8.399	10.968	2.569
73	1.218	0.628	0.519	1.147	-0.072			

The O&M equation is of the form $O\&M = \exp(aX - b MC)$. The partial derivative of O&M with respect to the MC rate is equal to $-b \exp(aX - b MC)$. To obtain the life-cycle cost saving per aircraft, we must first multiply the saving in O&M per flight hour by the annual usage rate (flight hours/aircraft/year). We assume a usage rate of 400 hours per year. We then sum this annual saving over an assumed 25-year aircraft life, using a discount rate of 4 percent per year.⁹ The result of this calculation is shown in the third column of Table 8.

The calculations thus far understate the benefits of reliability investments, because they ignore the operational value of having aircraft available a larger percentage of the time. To take this factor into account, suppose that N aircraft of this type are to be procured, at a unit procurement cost of \$P. Given an availability rate of MC, the number of effective aircraft is $N \times MC/100$.

⁹ Recall that O&M expenditures are already expressed in constant dollars, so discounting for future inflation would be redundant. We developed a real discount rate that reflects the time value of money over and above inflation. The real discount rate was measured by Moody's Aaa bond rate minus the GNP implicit price deflator. Over the past 15 years, this rate averaged 4.16 percent. We rounded to 4.0 percent for convenience.

Now consider a reliability investment that increases the availability rate to $MC' > MC$. If we continue to procure N aircraft, the number of effective aircraft increases to $N \times MC'/100$. Instead, we could use the improvement in availability to reduce the procurement quantity, thereby saving procurement funds while holding the number of effective aircraft at its initial level. To do so, we find a new procurement quantity, $N' < N$, such that:

$$N' \times MC'/100 = N \times MC/100$$

The solution to this equation is $N' = N \times (MC/MC') < N$. The saving in procurement funds is $\$P \times (N - N')$ which, upon substituting for N' , yields $\$P \times N \times (MC' - MC)/MC'$. We can obtain the saving on a per-aircraft basis after dividing by N , and we can consider a marginal change (i.e., an increase of a single MC point) by setting $MC' = MC + 1$. Under these conditions, the marginal saving on a per-aircraft basis is $\$P/(MC + 1)$.

Continuing our example, suppose that the aircraft has a base cost of \$30 million and a planned MC rate of 65 points (roughly the average values for carrier-based aircraft in our sample). An improvement in the MC rate to 66 points leads to procurement savings of $\$30/66 = \0.455 million per aircraft, as reported in the fourth column of Table 8. In computing the savings of a further improvement from 66 points to 67 points, two factors change. First, the denominator of the expression $\$P/(MC + 1)$ increases, tending to make the savings smaller. On the other hand, once we have invested \$0.94 million per aircraft in reliability improvements, the cost of the aircraft is no longer \$30 million but rather \$30.94 million. Hence, the procurement savings increase to $\$30.94/67 = \0.462 million.

To understand this result, recall that the procurement savings capture the benefits of purchasing fewer (but more available) aircraft. As we begin investing in an aircraft, the cost of the aircraft increases. But when the cost increases, the benefits of purchasing fewer aircraft are even more pronounced. Hence, the more we invest, the greater the incentive to continue investing. The O&M savings, however, decrease as we continue to invest. The decreasing O&M savings dominate the increasing procurement savings so that, as reported in the fifth column of Table 8, the overall benefits decline.

The sixth column of Table 8 shows the net benefit, computed by subtracting the marginal cost from the sum of the O&M savings and procurement savings. The net benefit remains positive through the row of the table corresponding to 72 MC points. Hence, an increase in the MC rate from 72 points to 73 points is cost-effective, but a further increase

from 73 points to 74 points is not. The optimal level of investment is that which brings the MC rate up to 73 points.

Table 8 also presents the cumulative costs and benefits of reliability investments, assuming again that the initial level of the MC rate is 65 points. An increase from 65 points to the optimal level of 73 points costs about \$8.4 million per aircraft. However, the life-cycle savings amount to nearly \$11 million per aircraft, yielding a net benefit of \$2.6 million per aircraft.

In this example, reliability investments serve to increase the unit procurement cost from \$30 million to \$38.4 million, or 28 percent. But the MC rate increases by 8 percentage points, or 12 percent. Hence the procurement quantity may be reduced by 12 percent without any sacrifice in the number of effective aircraft. The increase in total procurement cost is the net effect of these two changes, or about 14 percent. However, the savings in O&M costs over the life of the aircraft more than compensate for the increase in procurement cost¹⁰

B. ACTUAL AIRCRAFT

The same procedure may be used to compute the "optimal" MC rate for each of the eleven aircraft used to estimate the regression models. In performing this calculation, it must be kept in mind that the regression models are somewhat imprecise. The standard errors indicate that there is some uncertainty in the regression coefficients. Moreover, the moderate R-squared statistics (.511 in the MC rate equation, .672 in the O&M equation) indicate that the models do not fully capture all of the factors that determine the MC rate and O&M costs. Finally, the models are based on comparisons across aircraft. The models thus ignore idiosyncratic features of particular aircraft that may explain departures between observed MC rates and our calculated optimal rates.

Having noted these caveats, we present the observed and optimal MC rates in Table 9. For seven of the aircraft models, the optimal MC rate exceeds the observed MC rate by at least one point. The opposite is true for three other aircraft models, while for one aircraft model (F-15) the two rates are essentially equal.

¹⁰ For example, suppose the goal is to purchase 300 effective aircraft. Prior to the reliability investment, this goal requires that $300/.65 = 462$ aircraft be procured. The unit cost is \$30 million and the total cost is \$13.85 billion. After the reliability investment, only $300/.73 = 411$ aircraft need be procured. The unit cost is now \$38.4 million and the total cost is \$15.78 billion. The increase in total procurement cost is \$1.93 billion, or 13.95 percent. However, the life-cycle O&M savings for a fleet of 411 aircraft are \$2.92 billion.

Table 9. Observed and Optimal Levels of MC Rate
(Real Discount Rate = 4%)

Aircraft	Total Procurement Cost (100th unit)	Observed MC Rate	Optimal MC Rate
Navy/Marine Corps			
A-6E	31.31	65	73
A-7E	14.11	64	67
AV-8B	22.99	74	60
F-14A	38.06	63	82
F/A-18	54.60	68	79
S-3A	40.94	64	73
Air Force			
A-10A	13.83	82	58
F-15	34.62	77	76
F-16	26.61	82	67
F-111	44.19	70	81
EF-111A	29.06	68	80

One regularity emerges from Table 9. The correlation between unit cost and the difference between the optimal and observed MC rates is .659. Hence, reliability improvements are more desirable for the more expensive aircraft.

To understand this pattern, recall that the marginal procurement saving per aircraft is $\$P/(MC + 1)$. Hence, the procurement saving is larger for the more expensive aircraft. For these aircraft, it is cheaper to increase the number of effective aircraft through reliability improvements than through increasing the procurement quantity. For example, the optimal MC rate is much higher than the observed MC rate for the F-14A, a relatively expensive aircraft. Conversely, the optimal MC rate is much lower than the observed MC rate for the A-10A, the least expensive aircraft in our sample. With inexpensive aircraft, it may be cheaper to simply procure a larger quantity than to invest in reliability.

VII. CONCLUSIONS

We have estimated the marginal costs of improving aircraft availability through increased spending in either the development or procurement phases of an aircraft program. Our results indicate that MC rates of fleet aircraft are insensitive to development costs expended prior to the aircraft model's IOC. By contrast, MC rates are quite responsive to increases in unit procurement costs.

There are several possible explanations for the insensitivity of MC rates to early development expenditures. Most RDT&E dollars are spent on problems other than R&M. These RDT&E dollars could conceivably improve R&M, if they were specifically earmarked for that purpose. Instead, R&M problems that arise in the field are often attacked using procurement dollars. Therefore, part of the expected effect of development cost on MC rates may show up indirectly through procurement cost.

Two major benefits accrue to improved aircraft availability. The first benefit is the life-cycle saving in O&M costs that results from improved availability. This effect is substantial; we estimated that each one-point increase in the MC rate is associated with a reduction in O&M cost of about 7 percent.

In addition, higher availability enables a reduction in procurement quantity with no sacrifice in the number of effective aircraft. This effect is especially pronounced for the more expensive aircraft models. For those aircraft, it is cheaper to increase the number of effective aircraft through reliability improvements than through increasing the procurement quantity.

We combined our results on costs and benefits in a simulation exercise, to determine the optimal level of reliability investment for a hypothetical aircraft model. In this simulation, an increase in the MC rate from 65 points to the optimal level of 73 points costs about \$8.4 million per aircraft. However, the procurement saving plus the life-cycle O&M saving amount to nearly \$11 million per aircraft, yielding a net benefit of \$2.6 million per aircraft.

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APPENDIX A.
ANNUAL DATA

APPENDIX A.

ANNUAL DATA

The following table presents annual data on the MC rate, O&M per flight hour, and flight hours/aircraft/year.

Table A-1. Annual Utilization Data by Aircraft Model

Aircraft	Year	MC Rate	O&M Per Flight Hour (thousands of FY 1991 \$)	Flight Hours/Aircraft/ Year
A-6E	1981	53.7	2.571	601.1
	1982	55.3	2.606	554.6
	1983	61.7	2.455	564.0
	1984	62.8	2.229	503.4
	1985	64.1	2.457	631.1
	1986	67.1	3.195	470.0
	1987	72.6	2.104	406.5
	1988	70.5	2.662	419.4
	1989	73.9	2.463	449.6
A-7E	1981	55.5	1.736	493.0
	1982	57.7	1.831	438.7
	1983	58.4	1.689	481.5
	1984	65.4	1.721	445.7
	1985	63.3	2.193	528.8
	1986	66.2	2.430	422.9
	1987	70.8	1.871	428.6
	1988	66.9	1.556	514.7
	1989	71.0	1.418	431.9
AV-8B	1984	70.9	0.417	18.8
	1985	79.8	0.430	134.9
	1986	77.1	0.330	255.8
	1987	71.6	2.110	311.0
	1988	73.2	1.120	315.1
F-14A	1989	70.8	0.930	228.8
	1981	49.2	3.214	350.7
	1982	52.9	3.444	318.5
	1983	55.8	2.857	360.8
	1984	62.1	2.942	403.9
	1985	64.6	3.031	482.7

Table A-1. Annual Utilization Data by Aircraft Model (Cont.)

Aircraft	Year	MC Rate	O&M Per Flight Hour (thousands of FY 1991 \$)	Flight Hours/Aircraft/ Year
F/A-18	1986	68.8	2.399	351.1
	1987	71.8	3.082	324.0
	1988	69.9	3.222	375.0
	1989	68.6	2.536	425.6
	1982	58.9	2.769	354.8
	1983	61.7	0.468	279.4
	1984	65.6	0.207	462.9
	1985	65.4	3.886	342.2
	1986	69.4	0.826	304.5
	1987	72.1	2.358	354.0
S-3A	1988	77.3	1.608	373.9
	1989	74.7	1.402	334.3
	1981	39.7	2.190	474.2
	1982	49.8	2.597	447.0
	1983	56.7	2.174	453.6
	1984	64.3	1.978	546.2
	1985	75.5	3.147	554.5
	1986	77.7	2.361	441.7
	1988	76.5	3.989	397.0
	1989	75.3	3.927	429.0
A-10A	1983	76.1	1.123	581.4
	1984	79.8	1.030	589.6
	1985	82.3	0.969	585.8
	1986	82.6	0.901	573.0
	1987	83.4	0.873	581.6
	1988	86.1	0.792	550.7
	1989	84.4	0.703	649.9
F-15	1983	63.9	4.171	307.0
	1984	73.0	3.655	300.9
	1985	78.7	3.231	315.5
	1986	79.2	2.836	322.3
	1987	81.9	2.673	330.2
	1988	81.2	2.192	329.7
F-16	1989	79.5	2.117	366.2
	1983	70.5	2.063	296.9
	1984	78.3	1.787	363.8
	1985	82.2	1.777	352.4
	1986	85.4	1.780	370.5
	1987	85.8	1.553	391.6
	1988	86.4	1.305	391.7
	1989	83.3	1.083	542.2

Table A-1. Annual Utilization Data by Aircraft Model (Cont.)

Aircraft	Year	MC Rate	O&M Per Flight Hour (thousands of FY 1991 \$)	Flight Hours/Aircraft/ Year
F-111	1983	61.6	4.593	280.5
	1984	65.3	4.037	287.7
	1985	69.1	3.776	282.7
	1986	69.5	2.261	295.4
	1987	73.8	2.170	314.9
	1988	75.7	1.967	303.4
	1989	72.9	1.984	286.8
EF-111A	1983	55.4	3.084	266.1
	1984	64.8	2.362	276.0
	1985	68.5	2.200	290.4
	1986	68.9	1.930	328.0
	1987	75.0	2.318	304.3
	1988	74.7	2.026	323.9

APPENDIX B.

STATISTICAL ISSUES

APPENDIX B.

STATISTICAL ISSUES

LINEARIZATION OF MC FUNCTION

It would be inappropriate to model the MC rate as a linear function of aircraft characteristics. Although observed MC rates are at most 100 percent, a linear function might predict MC rates above 100 percent for aircraft with sufficiently favorable characteristics.

Instead, we used the exponential function $MC = f(X) = 100[1 - \exp(-b_0 - b_1X)]$, where X is a vector of aircraft characteristics, b_1 is a vector of coefficients, and b_0 determines the intercept. Specifically, the exponential function has intercept $100[1 - \exp(-b_0)]$. The exponential function is strictly increasing and concave in the product b_1X , and approaches the limit 100 as b_1X approaches infinity.

The partial derivative of the exponential function with respect to a particular aircraft characteristic, X_j , is not simply equal to the corresponding coefficient, b_j . Rather, it is equal to $100 b_j \exp(-b_0 - b_1X) = (100 - MC) b_j$. This quantity is often evaluated at the sample mean of MC.

It is possible to transform the exponential function so that the resulting regression equation is linear in the unknown coefficients. Define $Y = g(MC) = -\ln[1 - (MC/100)]$. Then Y may be expressed as $b_0 + b_1X$, a linear regression. Hence, our procedure is to compute Y for each data point, then regress the set of Y values on the set of X values to obtain estimates of b_0 and b_1 .

INTERCEPT CORRECTION FACTOR

The regression estimated in the previous section provides a linear predictor of $Y = g(MC)$ for any set of aircraft characteristics, X . Although the regression is estimated using Y rather than MC as the left-hand variable, it is often desired to predict the value of MC itself. Applying an inverse transformation from Y back to MC provides one estimate,

$MC = 100[1 - \exp(-Y)] = 100[1 - \exp(-b_0^* - b_1^*X)]$, where asterisks indicate the estimated regression coefficients. Unfortunately, this estimate is biased due to the non-linearity of the transformation.¹ However, we have derived a simple correction that removes the bias, at least in large data samples.

By regressing the transformed variable Y on the aircraft characteristics X , we are implicitly assuming that the data are normally distributed when measured on the Y -scale. The data on this scale have mean $m = b_0 + b_1X$ and variance denoted v . We are interested in estimating the mean MC rate associated with a given set of aircraft characteristics, $E(MC|X) = 100\{1 - E[\exp(-Y)|X]\}$. Because Y is normally distributed, it is well-known that the moment-generating function of Y is:² $E[\exp(tY)] = \exp(tm + t^2v/2)$ where t is a scalar parameter. In particular, setting $t = -1$ reveals that $E[\exp(-Y)] = \exp(-m + v/2) = \exp(-b_0 - b_1X + v/2)$.

A sample estimate is obtained by replacing m with $b_0^* + b_1^*X$ and v with the residual variance of the regression estimated on the Y -scale: $E^*(MC|X) = 100[1 - \exp(-b_0^* - b_1^*X + v^*/2)]$. This estimate is downward-biased in small samples (i.e., it over-corrects), but the bias disappears because the estimate is consistent in large samples. To see the small-sample bias, note that the function $E^*(MC|X)$ is concave in the regression estimates b_0^* and b_1^* , and the regression estimates are themselves unbiased, $E(b_0^*) = b_0$ and $E(b_1^*) = b_1$. Applying Jensen's inequality,³ $E[E^*(MC|X)] < 100\{1 - \exp[-E(b_0^*) - E(b_1^*)X + v/2]\} = 100[1 - \exp(-b_0 - b_1X + v/2)] = 100\{1 - E[\exp(-Y)]\} = E(MC)$. However, it follows from Slutsky's theorem⁴ and the continuity of the function $E^*(MC|X)$ that $\text{plim}[E^*(MC|X)] = 100[1 - \exp(-b_0 - b_1X + v/2)] = 100\{1 - E[\exp(-Y)]\} = E(MC)$.

DUMMY VARIABLES FOR AIRCRAFT MODEL

We stated in the main text that, with time-invariant aircraft characteristics present in the equation, inclusion of dummy variables for aircraft model would lead to perfect collinearity. To see this point, assume (with no loss of generality) that the observations are

1 This bias is similar to the well-known prediction bias in log-log regression models; see Duan [A-1]. The correction factor that we derive below is analogous to the so-called Ping factor often applied in log-log models.

2 See DeGroot [A-2], p. 219.

3 See DeGroot [A-3], p. 97.

4 See Dhrymes [A-4], p. 111.

sorted by aircraft model. To reduce notation, again with no loss of generality assume that the N aircraft models each contribute an equal number, T , of observations to the sample.

The intercept in the equation is represented in the data matrix by a vector of 1's, $q = (1, \dots, 1)$; this vector has length NT . Let v_1 denote a vector of 1's of length T , and let v_0 denote a vector of 0's also of length T . A dummy variable for aircraft n ($n = 2, \dots, N$) is represented in the data matrix as the following vector of length NT : $d_n = (v_0, \dots, v_0, v_1, v_0, \dots, v_0)$, where the sub-vector v_1 follows $n - 1$ sub-vectors v_0 .

Finally, consider a time-invariant characteristic that assumes the value f_n for aircraft n ($n = 1, \dots, N$). Array this characteristic into the following vector of length NT : $f = (f_1, \dots, f_1, f_2, \dots, f_2, \dots, f_N, \dots, f_N)$, where there are T repetitions for each aircraft.

(U) We will now demonstrate that f may be represented as a linear combination of the intercept (q) and the $N-1$ dummy variables (d_2, \dots, d_N):

$$\begin{aligned} & f_1 q + \sum_{n=2}^N (f_n - f_1) d_n \\ &= f_1 (q - \sum_{n=2}^N d_n) + \sum_{n=2}^N f_n d_n \\ &= f_1 d_1 + \sum_{n=2}^N f_n d_n \\ &= \sum_{n=1}^N f_n d_n = f. \end{aligned}$$

Hence, the variables are perfectly collinear, and the estimation procedure fails.

INSTRUMENTAL VARIABLES ESTIMATION

We estimate a system of two regression equations. The first equation expresses the MC rate as a function of aircraft characteristics, $MC = f(X) + u_1$, where u_1 is an error term reflecting factors not measured among the characteristics X . The second equation expresses operations and maintenance dollars per flight hour as a function of the MC rate and a vector Z of additional variables, $OM = h(MC, Z) + u_2$. In this equation, u_2 is an error term reflecting factors not measured among either MC or Z .

A regression model is intended to measure causation flowing from the right-hand variables to the left-hand variable. In the second equation of our system, a higher MC rate

reflects a more reliable aircraft, hence OM should be lower. That is, we expect a negative coefficient on MC in the second equation.

On the other hand, increases in OM can compensate for otherwise poor reliability. Hence, there is reverse causation flowing from OM (the left-hand variable) to MC (a right-hand variable). Moreover, because increases in OM lead to *increases* in MC, the effect of OM on MC differs in sign as well as causation from the effect of MC on OM. The negative coefficient that we expect on MC in the second equation is offset and possibly even overturned by the reverse causation.

More formally, the coefficient on MC in the second equation is biased because MC is "endogenous," i.e., MC is correlated with the error term u_2 in the second equation. Suppose that MC is initially held fixed but OM is increased; from the second equation, it is evident that this experiment is equivalent to an increase in u_2 . Reverse causation implies a response in which MC increases as well. Hence, MC and u_2 must be positively correlated.⁵

This problem is alleviated by replacing MC with a proxy variable that is highly correlated with MC, yet uncorrelated with the error term u_2 (by the latter condition, the proxy variable is "exogenous"). A proxy variable satisfying these requirements is said to be an instrumental variable⁶ for MC. A natural instrumental variable is given by the predicted value of MC from the first equation, $E^*(MC|X)$. This variable is clearly correlated with MC, particularly if the first equation has a high R-squared statistic. Moreover, the instrumental variable is a linear combination of the non-stochastic elements of X. Hence the instrumental variable is itself non-stochastic, and thereby uncorrelated with the error term u_2 .

The instrumental variable is interpreted as a "benchmark" level of availability, as determined solely by aircraft characteristics. This variable reflects the intrinsic availability of the aircraft, and is unaffected by compensating maintenance actions in the field. Stated

⁵ Our two equations have a "triangular" structure: both OM and MC appear in the second equation, but only MC appears in the first equation. It is sometimes thought that this structure renders least-squares estimates unbiased. In fact, unbiasedness requires in addition that u_1 and u_2 be uncorrelated. The combination of triangularity and zero correlation defines a "recursive" structure. We have already argued that MC and u_2 are correlated; hence u_1 , being the stochastic part of MC, must be correlated with u_2 . The distinction between triangular and recursive structures was first emphasized by Lahiri and Schmidt [A-5].

⁶ The use of instrumental variables to circumvent reverse causation is discussed in Greene [A-6], p. 621.

differently, the instrumental variable is uncontaminated by the reverse causation that leads to biased estimates when using the raw MC rate in the second regression.

AUTOCORRELATION CORRECTION FACTOR

Our two regression equations are estimated from data on several aircraft over several years each; for example, $OM_{jt} = Z_{jt}b + u_{jt}$, where j indexes aircraft and t indexes years. It is likely that the successive error terms for a particular aircraft (u_{j1}, u_{j2}, \dots) are correlated. Suppose, for example, that one aircraft has higher OM than predicted by the model in year 1970. This positive residual is likely to persist into subsequent years, so that the sequence of residuals is positively correlated. Similarly, an aircraft that persistently has lower OM than predicted by the model will have a sequence of negative residuals, which are nonetheless *positively* correlated.

Autocorrelation in the residuals does not lead to biased coefficient estimates, but does lead to inefficiency (i.e., larger standard errors and lower significance levels). There are well-known procedures for both measuring the degree of autocorrelation, and correcting the problem to secure efficient estimates. However, these procedures must be modified when the data set consists of pooled time-series on several observational units (i.e., on several aircraft models).

The conventional procedure arrays all of the residuals into a single sequence, and compares all adjacent pairs of residuals to measure the degree of autocorrelation. In our context, however, it makes no sense to compare the final residual for one aircraft with the initial residual for the next aircraft. Instead, we compute an autocorrelation coefficient by considering only pairs of residuals for the *same* aircraft.⁷ Specifically, we compute:

$$r = \sum_j \sum_t u_{jt} u_{j, t-1} / \sum_j \sum_t u_{jt}^2$$

Then, following conventional procedure, estimation is performed on the transformed variables $(OM_{jt} - r OM_{j, t-1})$ and $(Z_{jt} - r Z_{j, t-1})$.

⁷ This procedure is suggested by Greene [A-6], p. 473.

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